

The interplay between radio jets and ISM in sub-kpc radio sources

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Abstract.

This paper reviews the evidence for interaction between radio jets and their environment in small (sub-kpc) and intermediate scale radio sources. Observations of gas (both neutral hydrogen and ionised gas) have shown the presence of fast (> 1000 km/s) outflows likely originating from this interaction. The characteristics of these AGN-driven outflows (e.g. mass outflow rate) indicate that they may have a relevant impact on the evolution of the host galaxy. We also report on the detection of large HI disks found around the host galaxies of nearby compact radio sources. Similar structures have so far not been detected around large radio sources. The presence of these structures in relation to the evolution of young compact radio sources is discussed.

1. Interaction between the radio jets and the ISM: why is important?

In a hierarchical scenario, galaxy mergers play a major role in the formation of early-type galaxies and they may also provide the way to bring gas to the central regions, fuel the super-massive black hole (SMBH) and make it active. However, the hierarchical scenario would not fully explain the properties of the observed structures unless strong feedback occurs dumping large amount of energy on the interstellar and intergalactic medium. The onset of the quasar activity (including the radio-loud phase) is now considered as one of the important source of feedback, driving gas out of the central regions of galaxy, regulating star formation and the growth of the SMBH (Silk & Rees 1998; Fabian 1999; di Matteo et al. 2005; Hopkins et al. 2005). Thus, *the initial phase of AGN can be crucial in the evolution of the host galaxy.*

In the radio-loud phase of the AGN, radio jets and the surrounding interstellar medium (ISM) can interact and affect each others. If the ISM is rich and dense, the effect of the surrounding medium on the radio jet can, for example, momentarily disrupt the jet but it can also frustrate or destroy it. On the other hand, the radio jets may have a profound influence on the medium. It can produce gas outflows that could clear the circum-nuclear regions. Thus, the interaction between radio-jets and ISM is one of the possible mechanisms for triggering outflows (together with radiation pressure and starburst winds). The radio jets can, therefore, provide one of the source of feedback. How relevant these outflows are, is the topic of this paper.

In radio-loud objects, we know which one are *young* AGN. Based on their size and on the characteristics of their radio spectrum, these are the so-called GigaHertz Peaked and the Compact Steep Spectrum (GPS/CSS) sources (with possibly the High Frequency Peaker being an even young example of radio sources, see Orienti et al. these Proceedings). A more detailed description of the characteristics of GPS/CSS is given by Giroletti in these Proceedings. We can, therefore, use CSS and GPS radio sources to study their effect on the surrounding medium. In particular, we use the kinematics of the gas to trace what is happening in the central regions of these radio-loud, active galaxies. We will focus on atomic neutral hydrogen and ionised gas: these two phases of the gas are given complementary information and therefore they are both important in order to obtain a full picture of what is happening. The molecular gas has been nicely discussed in Patrick Ogle's talk.

Before starting, let me remind you that gas in the centre of early-type (field) galaxies - the typical host galaxies of the radio-loud objects discussed here - is an important and common component. In general, ionised gas is detected in the central region of about 70% of early-type galaxies (see e.g. Sarzi et al. 2006). The kinematics of this gas is often complex, e.g. with kinematical decoupled cores. This suggests that in most of the cases (although not in all!) the external origin of the gas is the most likely. For the neutral hydrogen, we will mainly concentrate on gas detected via HI absorption that for radio-loud objects allows to explore the small scales, circum-nuclear regions. In radio galaxies, HI absorption detected against their radio cores and likely associated with their circum-nuclear region is relatively common. HI emission is more difficult to be detected at the typical distance of radio galaxies (but see Sec. 4 for some discussion of HI emission for nearby radio galaxies). On the large scale, the HI in emission and the ionised gas appear to be part of the same structure as they show the same kinematic, often decoupled from the one of the stars (Morganti et al. 2006).

2. What are the characteristics of the circum-nuclear gas in CSS/GPS radio sources?

In the case of young compact radio sources (CSS/GPS), we would like to answer a number of questions, among which:

- Are the jets of these young radio sources really moving through a dense medium?
- How the characteristics of this gas compare to what found in large radio galaxies?
- What is the kinematics of the gas? Do we see evidence of the interaction between the radio jets and the medium (e.g. outflows)?

2.1. The atomic neutral hydrogen

From HI absorption observations, we know that CSS/GPS sources have typically an high detection rate (compared to extended radio sources), as reported by Vermeulen et al. (2003); Gupta et al. (2006) - although this does not appear to

be the case for the even smaller (and younger) HFP (see Orienti et al. 2006, for possible explanations). CSS and GPS sources also appear to have often an higher optical depth (and column density) of the HI compared to what detected in large radio sources.

The HI absorption in CSS/GPS shows often a relatively narrow component (100-200 km/s FWHM), similar to what found against the nucleus of many extended radio galaxies. However, in addition to this, we have recently found also cases of very broad HI component. Using the Westerbork Synthesis Radio Telescope (WSRT) we have detected these very broad HI absorption components in a number of radio galaxies as reported in Morganti et al. (2005a). An example of the broad HI absorption (for the radio galaxy 3C 305) is shown in Fig. 1 and discussed below. The broad component is typically mostly blueshifted, therefore indicating outflowing gas. The objects showing this broad HI component are characterised by the presence of a rich ISM surrounding the AGN, e.g. strong CO or far-IR emission, and/or known to have undergone a major episode of star formation in the recent past (Tadhunter et al. 2005). Some of them have strong, steep-spectrum core emission (on a scale <10 kpc, i.e. unresolved at the resolution of the WSRT 21-cm observations). These objects are considered to be young or recently restarted radio sources (see e.g. 3C 293 and 3C 236).

2.2. The ionised gas

Interestingly, in the same objects outflows with similar characteristics to the one in neutral hydrogen have been detected also in ionised gas. Holt (2005) and Holt et al. (in prep) have studied the characteristics of the optical emission lines in compact (GPS/CSS) and extended radio galaxies. Of the 14 powerful CSS/GPS studied (selected from the 3C/4C-2Jy samples), 11 show evidence for fast outflows indicated by the presence of blueshifted components in the compact sources more than in the extended. The distributions of the velocities of the components are clearly different, with the compact radio sources containing more extreme outflows than their extended counterparts. Indeed, this trend is also evident within the sample of compact radio sources, with the two highest outflow velocities observed in some of the smallest (GPS) radio sources. The distributions were tested using a Kolmogorov-Smirnov test and were found to be different at the 99.9% confidence level. Hence, radio source size is clearly important in determining the outflow velocity of the emission line gas (Holt et al. 2007, in prep).

2.3. The location of the HI outflow: the case of 3C 305

In order to understand whether the radio jet plays an important role in the origin of the gas outflows described above, it is important to identify the location of the outflows. Because the radio sources we are interested in are small, this is not an easy task. We have now this information for a handful of sources. In the case of the CSS 3C 305, high-spatial resolution 21-cm HI VLA observations have been obtained. These high-resolution data show that the ~ 1000 km s $^{-1}$ broad HI absorption, earlier detected in low-resolution WSRT observations, is occurring against the bright, eastern radio lobe, about 1.6 kpc from the nucleus (see Fig. 1). The broad HI absorption has a column density 2×10^{21} cm $^{-2}$ (for $T_{\text{spin}}=1000$ K). The mass outflowing gas is estimated $\sim 10^6$ M $_{\odot}$.

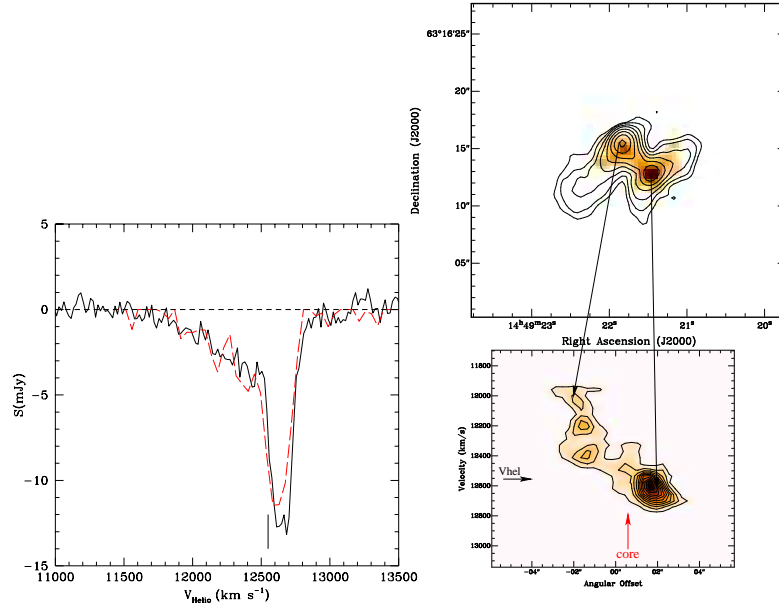


Figure 1. (Left) HI absorption profile obtained with the WSRT (solid line) superimposed to the integrated spectrum from the - high spatial resolution - VLA observations (long-dashed). The profile shows a deep, relatively narrow, absorption and a broad component that covers more than 1000 km s^{-1} at zero intensity and mostly blueshifted compared to the systemic velocity that is indicated. (Right) Panel showing (Top) the radio continuum image (contour) and the integrated HI absorption (grey scale) from the VLA data. (Bottom) The position-velocity plot from a slice passing through the two lobes. The grey scale image represents the total intensity of the HI absorption (see Morganti et al. 2005a, for details).

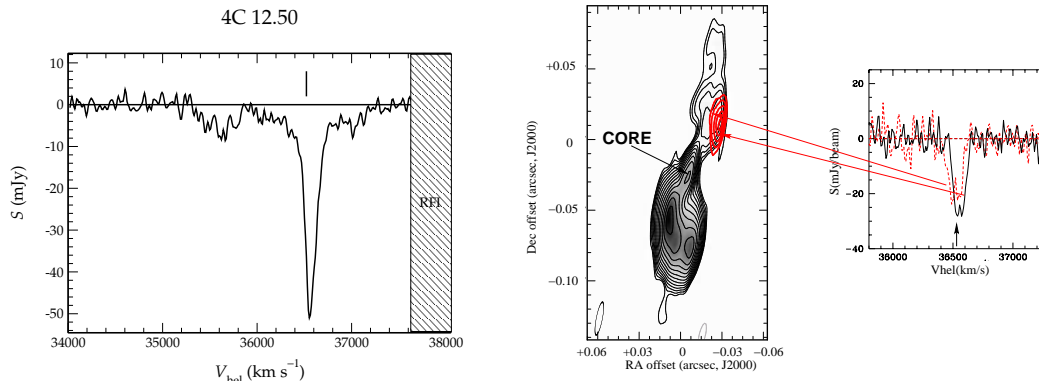


Figure 2. *Left* HI absorption profile of 4C12.50 as derived from WSRT observations. The broad, blueshifted component is clearly seen. *Right* VLBI image of 4C12.50 and of the location of the narrower HI absorption component (Morganti et al. 2004).

Earlier studies of the ionised gas had already found evidence for a strong interaction between the radio jet and the interstellar medium at the location of the eastern radio lobe (Jackson et al. 2003). Our results show that the fast outflow produced by this interaction also contains a component of neutral atomic hydrogen. The most likely interpretation is that the radio jet ionises the ISM and accelerates it to the high outflow velocities observed. Our observations demonstrate that, following this strong jet-cloud interaction, not all gas clouds are destroyed and that part of the gas can cool and become neutral (Krause 2007, see also e.g.).

In addition to 3C 305 we have a few more objects where we know the gas outflow (both neutral hydrogen and ionised gas) is happening off-nucleus. We have interpreted all these outflows as due to *interaction between that radio jet and the ISM* (see Morganti et al. 2005b, for more details).

2.4. The mass outflow rate

Mass outflow rates were calculated for all the galaxies where fast HI outflows have been detected (see Morganti et al. 2005a, for details).

As mentioned above, the main result of this study is that the neutral outflows occur, in at least some cases, at kpc distance from the nucleus, and they are most likely driven by the interactions between the expanding radio jets and the gaseous medium enshrouding the central regions. We estimated that the associated mass outflow rates are up to $\sim 50 M_{\odot} \text{ yr}^{-1}$, comparable (although at the lower end of the distribution) to the outflow rates found for starburst-driven superwinds in Ultra Luminous IR Galaxies (ULIRG), see Rupke et al. (2002). This suggests that massive, jet-driven outflows of neutral gas in radio-loud AGN can have as large an impact on the evolution of the host galaxies as the outflows associated with starbursts. This is important as starburst-driven winds are recognized to be responsible for inhibiting early star formation, enriching the ICM with metals and heating the ISM/IGM medium.

3. A detailed study of two objects

3.1. The extreme gas outflow in the GPS source 4C 12.50

As discussed in detail by Holt et al. (2003) and Morganti et al. (2004), PKS 1345+12 is probably the best example of young radio galaxies showing extreme gas outflow both in neutral hydrogen and ionised gas. At the position of the nucleus we observe complex emission line profiles and Gaussian fits to the [OIII] emission lines require three components (narrow, intermediate and broad), the broadest of which has width 2000 km s^{-1} (FWHM) and is blueshifted by 2000 km s^{-1} with respect to the halo of the galaxy and the narrow HI absorption. We interpret this blueshifted component as material in outflow. We also find evidence for large reddening [$0.92 < E(B-V) < 2.00$] and high densities ($n_e > 4200 \text{ cm}^{-3}$) for the most kinematically disturbed component (see Holt et al. 2003, for details).

Interestingly a similarly broad component is observed in HI absorption (see Fig. 2). The location of the broad HI outflow is not known yet. However, a VLBI study of the neutral hydrogen in the nuclear regions of this object shows that the narrower HI component (detected close to the systemic velocity) is associated with an off-nuclear cloud (~ 50 to 100 pc from the radio core, see Fig. 2) with a column density of $\sim 10^{22} T_{\text{spin}}/(100 \text{ K}) \text{ cm}^{-2}$ and an HI mass of a few times 10^5 to $10^6 M_{\odot}$. A number of possibilities have been considered to explain the results. In particular, this cloud appears to indicate the presence of a rich and clumpy interstellar medium in the centre, likely left over from the merger that triggered the activity and that this medium influences the growth of the radio source. The location of the cloud – at the edge of the northern radio jet/lobe – suggests that the radio jet might be interacting with this gas cloud. This interaction could be responsible for bending the young radio jet (see Morganti et al. 2004, for details). We argue that PKS 1345+12 is a young radio source with nuclear regions that are enshrouded in a dense cocoon of gas and dust. The radio jets are expanding through this cocoon, sweeping material out of the nuclear regions.

3.2. PKS 1549-79: an example of radio source in the early-stage of its evolution

The compact radio source PKS 1549-79 provides the best example that in the initial growth phase, the black hole is substantially obscured at optical wavelengths in this object, consistent with recent galaxy evolution models (Holt 2005). We use deep optical, infrared and radio observations to explore the symbiosis between nuclear activity and galaxy evolution in this compact radio source (see Holt et al. 2006, and ref. therein for more details). The optical images reveal the presence of tidal tail features which provide strong evidence that the host galaxy has undergone a major merger in the recent past. The merger hypothesis is further supported by the detection of a young stellar population (YSP), which, on the basis of spectral synthesis modeling, was formed 50-250 Myr ago and makes up a significant fraction of the total stellar mass (1-30 per cent).

Despite the core-jet structure of the radio source, which is consistent with the idea that the jet is pointing close to our line of sight, our HI 21-cm observations reveal significant HI absorption associated with both the core and the jet, see Fig.3 and Holt et al. (2006). No broad permitted (optical) lines are detected

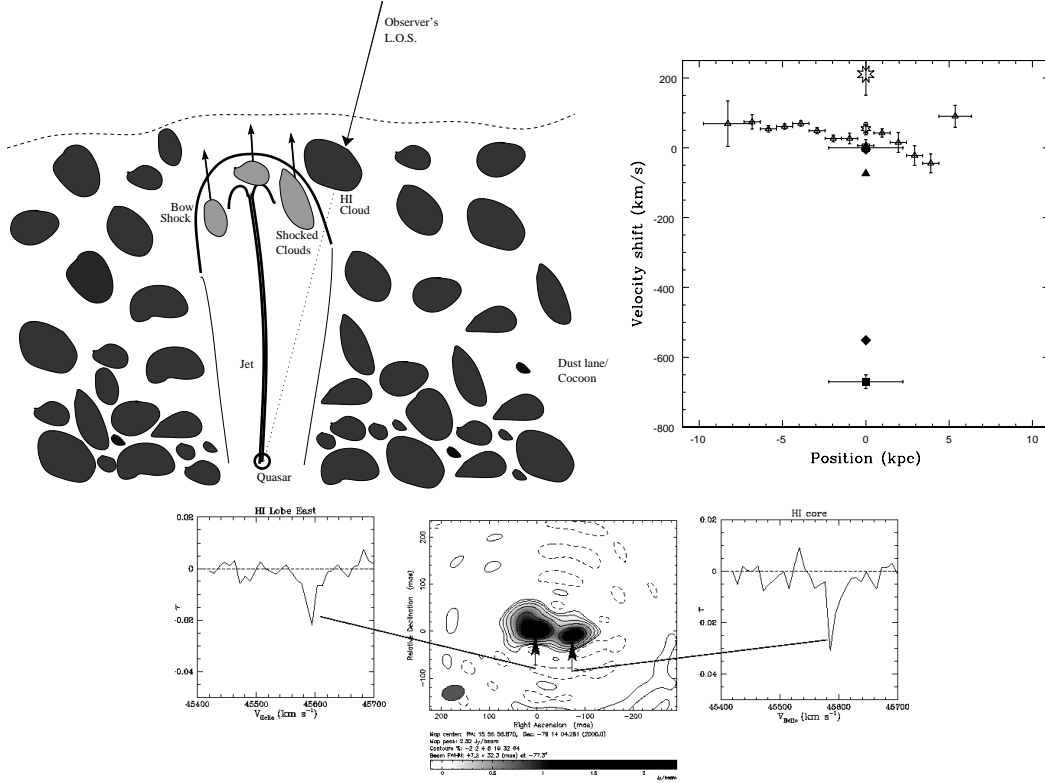


Figure 3. (*Top-left*) Cartoon representing the possible geometry arrangement for the various emitting components in PKS 1549-79 (see Holt et al. 2006, for details). The [OIII]-emitting clouds are shaded light grey, most of the [OII] is emitted by material in the extended disk/cocoon (shaded light grey). (*Top-right*) Radial velocity profiles of the optical emission lines of PKS 1549-79. Small open and filled triangles represent the narrow and intermediate components of H α respectively (symbols described in Holt et al. 2006). Over-plotted is the radial velocity of the deep HI 21cm absorption (large filled triangle at -30 km s^{-1} from Morganti et al. (2001)). (*Bottom*) HI absorption from the VLBI data of PKS 1549-79. This shows as the narrow HI component is undisturbed gas that surrounds the entire radio source (see Holt et al. 2006, for details).

but broad $\text{Pa}\alpha$ in NIR is observed. The optical lines (e.g. $[\text{O III}]\lambda 5007, 4959$ lines) are highly blueshifted ($\Delta V \sim 680 \text{ km s}^{-1}$) indicating the presence of a fast outflow.

We conclude that PKS 1549-79 is a radio source in a stage where the nucleus is still hidden (in the optical) by the gas/dust coming from the merger that triggered the radio source. Young, small scale radio jets are expanding through dense cocoon sweep aside gas and dust. The AGN driven outflow will eventually remove this gas. However, we find that the *warm-gas outflow* is small (mass outflow rates $0.12 < \dot{M} < 12 M_{\odot} \text{ yr}^{-1}$) and not as large as expected in the quasars feedback model (see Holt et al. 2007, for details). We are now investigating whether outflows of hot or cold gas may have a more significant impact.

4. Nearby compact radio galaxies

The objects described above are all powerful compact radio galaxies. For nearby ($z < 0.04$) lower luminosity, compact sources the situation could be different. It is interesting to look at the characteristics of very nearby compact steep spectrum as the one discussed by Giroletti these Proceedings.

Some of these objects are so close that HI in emission can be detected and studies. This was done as part of the observations of a large sample of nearby radio galaxies (Emonts et al. 2006). The remarkable trend found is that the radio galaxies with large amounts ($M_{\text{HI}} > 10^9 M_{\odot}$) of extended (many tens of kpc up to 200 kpc!) HI disks all have a compact radio source while such disks have not be found in extended radio sources (in particular in FR type-I radio galaxies). Fig. 4 shows an example of such huge HI structures and the plot illustrating how the very HI-rich structures are associated with sub-kpc radio galaxies.

This trend can be explained if the HI-rich compact radio sources do not grow into extended sources, either because frustrated by the ISM in the central region of the galaxy or because the fuel stops before the source expands. This would therefore support the idea (see also Giroletti these proceedings) that not all compact sources are young counterparts of the extended radio galaxies.

5. Summary of the results

The results presented here support the idea that a rich medium is often found around young radio galaxies. Broader and blueshifted optical emission lines are associated with such sources indicating that fast outflow of ionised gas are very common. High HI column density and fast HI outflows are detected and interpreted as produced by the interaction between the radio jet and the surrounding dense medium. Thus, in powerful compact sources the jet/ISM interaction is important and many effects are seen, including complex, stratified structure of the ionised gas outflow. The mass of the gas involved in the outflows does not seem to be large enough to frustrate the source but likely able of slowing down the evolution of the jets. Nearby low-luminosity compact sources may have a different evolution. Some of them may just fade away and do not grow to large size.

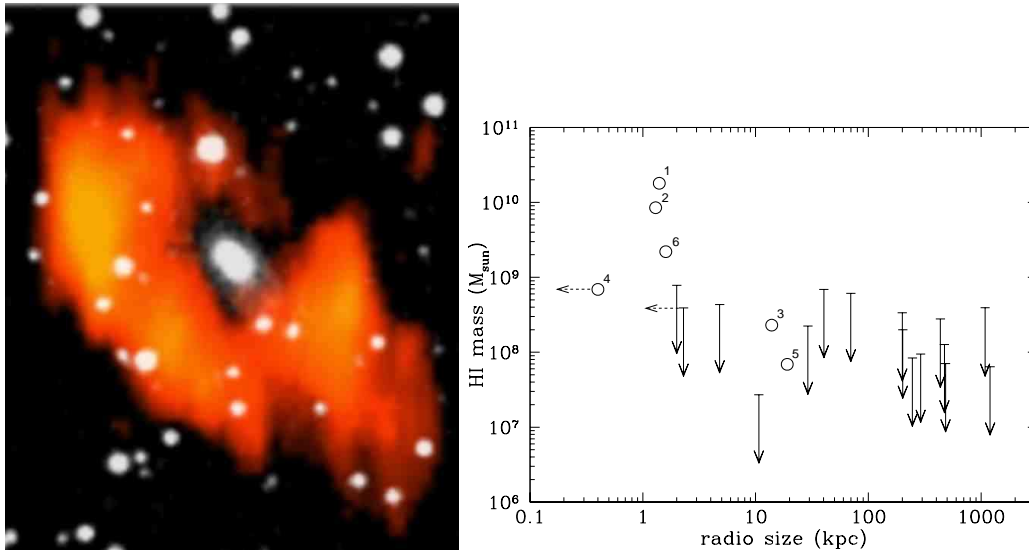


Figure 4. *Left* Total HI intensity (orange in the electronic version of the paper) superimposed to the optical image of B2 0648+25. *Right* Plot of the HI mass versus the size of the radio source: it shows as large amount of HI (mainly distributed in large disk structure) were detected only in compact kpc-scale sources. Figures taken from (Emonts et al. 2006)

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